

**AN ALTERNATE ANALYSIS METHOD FOR DETERMINING
STORAGE LIMITS AND INTERMAGAZINE SEPARATION
DISTANCES FOR NONSTANDARD EARTH-COVERED MAGAZINES**

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ABSTRACT

Large numbers of nonstandard earth-covered magazines are currently in use at Department of Defense installations, depots, and ammunition plants. An effort is currently underway to more accurately assess the blast resistance of these magazines. As a part of this effort, the U. S. Army Engineering and Support Center, Huntsville was tasked by the Department of Defense Explosives Safety Board to identify those nonstandard magazines that can be upgraded to higher storage limits without compromising explosive safety requirements. The results of this tasking are presented in this paper.

Under the tasking, a detailed survey was conducted of existing nonstandard earth-covered magazines. The results of the survey are outlined in this report, and the structural blast capacities of magazine headwalls and doors are reviewed and discussed. In addition, an alternate analysis method is presented for determining safe storage limits and intermagazine separation distances for these magazines. Initial analyses have shown that if only robust munitions are stored in the donor and acceptor magazines, the storage limit in the donor magazine may be increased and the intermagazine separation distances between the donor and acceptor magazines may be reduced. The paper concludes with a discussion of possible future applications of the alternate analysis method to nonstandard magazines storing non-robust munitions and with recommendations for future work.

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1.0 INTRODUCTION

In chapter 5 of the DOD Ammunition and Explosives Safety Standards, DOD 6055.9-STD [1], standard and nonstandard earth-covered magazines (ECM) are defined. In order to be designated as a standard ECM, a magazine either must be constructed in accordance with an approved drawing series or must be shown to be at least equivalent in strength to magazines constructed under these series. Standard ECMs are approved for all quantities of explosives up to 500,000 pounds net explosive weight (NEW) except for NAVFAC box-type C, D, E, and F magazines which are limited to 350,000 pounds NEW.

Nonstandard magazines are defined as ECMs whose construction is not equivalent in strength to the approved drawing series. Nonstandard magazines are approved for all quantities of explosives up to 250,000 pounds NEW.

In FY 1995, the U. S. Army Engineering and Support Center, Huntsville (CEHNC) was tasked by the Department of Defense Explosives Safety Board (DDESB) to perform analyses to identify those nonstandard magazines that can be safely upgraded to higher storage limits. The work performed under this study was an extension of previous work conducted by CEHNC for the DDESB. This work includes the recently updated "Guide for Evaluating Blast Resistance of Nonstandard Magazines." [2]

The design loadings provided in the CEHNC guide were developed from full and reduced scale tests of earth covered magazines performed under the ESKIMO (Explosive Safety Knowledge Improvement Operation) test program. In the guide, the structural analysis methods of TM 5-1300, "Structures to Resist the Effects of Accidental Explosions," are used to evaluate the adequacy of magazine headwalls to withstand the blast loading from a quantity of explosives at a known separation distance and relative orientation. The procedures provided employ allowable deformation criteria to determine the adequacy of blast resistant structural elements. For example, to prevent explosive propagation to munitions stored in an acceptor magazine, the maximum support rotation of the concrete headwall is limited to 12 degrees. [3] The headwall will always control the resistance of existing ECMs in the DOD inventory. In the ESKIMO test program, the arch itself and the rear wall were shown to be non-critical.

Under the FY 1995 study, site visits were made to Tooele Army Depot, Tooele, Utah; Hawthorne Army Depot, Hawthorne, Nevada; Sierra Army Depot, Herlong, California; Red River Army Depot, Texarkana, Texas; Camp Navajo, Albuquerque, New Mexico; and Fort Stewart, Georgia. An additional site visit was conducted to the U. S. Army Defense Ammunition Center and School in Savanna, Illinois to gather data on the types and quantities of munitions stored in DOD magazines.

The report is divided into two main sections. In the first section, the blast resistance of typical nonstandard magazines is determined using the current deformation based criteria of TM 5-1300. Structural data for the magazines are taken from drawings obtained through the site visits to the installations. In addition, storage limits are provided for several magazine types based on their actual site layout and construction.

In the second section, the development of an alternate analysis method is presented. The alternate method is based on preventing explosive propagation from a donor to an acceptor magazine. Under this method, the headwall of the acceptor magazine is allowed to fail. Secondary fragmentation from the headwall may impact the munitions in the acceptor magazine causing some physical damage (such as denting of the casings), but impact velocities are limited to a level which will not result in any reaction of the munitions. Munitions near the headwall may, however, suffer sufficient damage to be rendered unusable.

2.0 BLAST ANALYSIS OF NONSTANDARD MAGAZINES

2.1 Background Information

As mentioned in the previous section, site visits were conducted to Tooele Army Depot, Red River Army Depot, Camp Navajo, Fort Stewart, Hawthorne Army Depot, and Sierra Army Depot. Based on the results of these site visits, the nonstandard magazines at Tooele Army Depot and Red River Army Depot were selected for detailed analysis.

2.1.1 Tooele Army Depot

There are a total of 902 earth covered magazines at Tooele Army Depot. The magazines are constructed in three different lengths: 700 magazines are 81'-0" long, 200 magazines are 60'-8" long, and 2 magazines are 40'-4" long. All magazines except 100 of the 81'-0" long magazines were constructed in the early 1940's and have a single leaf door. The remaining 100 magazines were built in the early 1950's and have a double leaf door.

The 802 single door magazines were constructed in accordance with O.C.E. drawing series 652-1012 through 652-1014. This drawing series represents a redesign of the standard drawing series 652-686 through 652-693. The modified drawings were developed to conserve critical wartime construction materials. As a result, headwall reinforcing was reduced, the door was modified, the thickness of the headwall was reduced, and the ends of the headwall were stubbed (earth fill spilled around front corners). In the available literature, the magazines are often designated as Huntsville type. Similar magazines were constructed at Pueblo Army Depot, Black Hills Army Depot, Blue Grass Army Depot, Camp Navajo, and Sioux Army Depot. [4] Based on the large number in use, these magazines were chosen for detailed analysis.

The remaining 100 double door magazines were constructed using drawing series 33-03-51. The concrete headwalls are 12 inches thick, and both the door and headwall are supported by pilasters. Due to their substantial construction, these magazines were also selected for analysis; they should be representative of the higher end of blast capacities for nonstandard magazines using current deformation controlled analysis.

2.1.2 Red River Army Depot

There are a total of 702 earth covered magazines at Red River Army Depot. [5] The magazines are separated from each other in all directions by a minimum distance of 400 feet. All of the magazines were built in the early 1940's and have a single leaf door. The magazines were constructed in three different lengths: 400 magazines are 81'-0" long, 300 magazines are 60'-8" long, and 2 magazines are 40'-4" long.

The construction of the magazines appears to have been based upon standard drawing series 652-686 through 652-693. Based on the available drawings, the single leaf doors were fabricated using drawing 652-693, are concrete filled, and are very lightly reinforced. It is unclear what, if any, modifications were made to the standard design. Due to their large number and the potential impact on storage if explosive limits could be increased, the magazines were chosen for detailed analysis.

2.2 Blast Analysis of Tooele Army Depot Magazines

As previously mentioned, the nonstandard magazines at Tooele Army Depot were constructed in two phases. The 802 single door magazines were built in the early 1940's and followed drawing series 652-1012 through 652-1014. The remaining 100 double door magazines were constructed in the early 1950's using drawing series 33-03-51. All of the double door magazines were placed between existing single door magazines in "C" block.

2.2.1 Single Door Magazines (Drawing Series 652-1012 through 652-1014)

For all single door magazines except those in "C" block, the side to side separation distance between magazines is approximately 380 feet. The magazines are placed in rows with each row offset from adjacent rows by one half the side to side separation distance. This placement results in a minimum rear to front separation distance along a diagonal of 400 feet.

During the site visit, drawings 652-1012 and 652-1013 were found among the file drawings. No copy was located of drawing 652-1014, the drawing providing door design details. Instead, standard drawing 652-692 (Door Details - Steel Door) was found with the other drawings. The safety engineers at Tooele were uncertain which drawing was followed in fabricating the door. Since drawing 652-1014 was not available, blast analyses were performed using the structural properties of the stronger 652-692 door.

Airblast loadings on the magazine headwall were determined using the typical separation distances of 380 feet side to side and 400 feet rear to front. Accordingly, results of the analysis are applicable to magazines in all areas except "C" block. The magazine headwall, pilaster, and door were analyzed in accordance with TM 5-1300. The worst case loading was from the rear of a donor magazine to the front of an acceptor magazine.

For this type of magazine, the concrete headwall and pilaster have the lowest blast resistance. At the typical separation distances given above, the maximum allowable donor charge weight to

satisfy TM 5-1300 deformation limits is only 75,000 pounds NEW. Consequently, the current regulatory defined storage limits of 250,000 pounds for the magazine cannot be increased by analysis.

2.2.2 Double Door Magazines (Drawing Series 33-03-51)

As mentioned in section 2.2, the double door magazines were placed between existing single door magazines in "C" block. The resulting separation distances are approximately 180 feet side to side and approximately 360 feet rear to front.

The magazine headwall, pilaster, and door were analyzed in accordance with TM 5-1300. As with the single door magazines, the worst case loading was from the rear of a donor magazine to the front of an acceptor magazine. For this loading, all structural elements were able to withstand the standard magazine loading from the detonation of 500,000 pounds NEW.

However, the siting of the magazines prevents their designation as standard. The magazines on each side of the double door magazines are single door magazines. Considering the reduced separation distances, the maximum loading which the single door magazines can safely withstand based on the TM 5-1300 methodology will be less than 75,000 pounds NEW. As a result, even though the magazines can be sited for 500,000 pounds as an acceptor, the storage capacity must be limited because of their threat as a donor. Therefore, the storage limits for the double door magazines in this siting layout cannot be increased by analysis.

2.3 Blast Analysis of Red River Army Depot Magazines

As previously stated, there are a total of 702 earth covered magazines at Red River Army Depot (RRAD). The magazines were constructed in the early 1940's and appear to have been constructed in accordance with standard drawing series 652-686 through 652-693. The reason for the magazine's designation as nonstandard is unclear.

According to the drawings provided by RRAD, the doors into the magazines were built using standard drawing 652-693 and therefore primarily consist of a 4-inch thick slab of lightly reinforced concrete. Since concrete has a very low tensile capacity, the blast resistance of these doors is very low; at the 400 feet separation distances at RRAD, the explosive limit based on the door's deformation will be far less than 250,000 pounds.

Further analysis of these magazines using the deformation based methods of TM 5-1300 concluded that the blast resistance of the headwall and pilaster is limited to 200,000 pounds NEW. Consequently, even if the doors on the magazines are replaced, the explosive limit of the magazines cannot be increased by analysis.

3.0 ALTERNATE ANALYSIS METHOD

3.1 Introduction

The alternate analysis method is based on techniques developed from concurrent research and analyses conducted by CEHNC, the Naval Facilities Engineering Service Center (NFESC), and the Army Research Laboratory (ARL). The alternate method utilizes secondary fragmentation data from the CEHNC study, advanced munition body analysis techniques developed by NFESC, and explosive sensitivity data from ARL research to determine safe explosive limits for nonstandard magazines.

Under the CEHNC study, significant parametric data were developed on the response of 12-inch concrete substantial dividing walls (SDW) to airblast loading. [6] In the study, hydrocode analyses were performed on typical 12-inch SDWs subjected to blast loading from bare explosive charges. The hydrocode analyses provided new data on the velocity of wall fragments from a concrete wall following an explosive detonation. Using this information, an integrated method of analysis has been developed which yields conservative estimates of the maximum velocity of secondary wall fragments produced by the failure of a concrete wall. In the following paragraphs, the components of this methodology are discussed in further detail.

Under the Navy's High Performance Magazine (HPM) program, the NFESC and ARL are conducting extensive research on the explosive sensitivity of munitions. The results of their research are being used by the NFESC to develop design concepts for a new storage magazine. The new magazine will use nonpropagation walls of various materials to lower the maximum credible event in the magazine, thereby reducing the minimum separation distances to other magazines and facilities. [7]

As a part of their study, the NFESC and ARL have developed sympathetic detonation threshold criteria for a wide range of acceptor munitions. Munitions which will be stored in the high performance magazine have been divided into eight storage groups based on current storage compatibility groups, explosive sensitivity, weapon type, and damage mechanisms. Research is currently underway to determine the most sensitive, worst case explosive acceptor(s) in each storage group. This research includes an evaluation of munition sensitivity to secondary fragment impact.

3.2 Basis of Alternate Analysis Method

As discussed in the previous section, the alternate analysis method utilizes data on the secondary fragmentation debris threat from the magazine headwall and data on acceptor munition sensitivity to determine safe explosive limits for nonstandard magazines. Under the alternate analysis method, the headwall of an acceptor magazine is allowed to fail. The maximum velocity of secondary fragmentation from the headwall is determined using the procedures developed in the 12-inch SDW study. To illustrate, maximum debris velocities were calculated for concrete headwalls sited at the minimum standard magazine rear to front separation distance of $2.0 W^{1/3}$ and at the typical nonstandard magazine rear to front separation distance of 400 feet. Results are summarized in Tables 1 and 2.

For a given separation distance and explosive quantity, the calculated maximum headwall debris velocity is next compared to the data on the sensitivity of munitions of interest to secondary fragment impact developed under the HPM program. Through so doing, one can determine if propagation would occur if these munitions were stored in an acceptor magazine.

The alternate analysis method provides the potential to increase storage capacity for those acceptor magazines which store munitions with adequate strength to withstand the "worst case" fragmentation loading from the headwall. It should be noted that when it is used, the alternate method will only ensure that a detonation will not propagate from a donor to an acceptor magazine. Considerable damage, however, may occur to the munitions in the acceptor magazine, rendering some of the contents unusable. Therefore, asset protection must be a consideration of the controlling command.

Under the HPM program, the NFESC has developed threshold criteria for the minimum peak pressure on a munition's explosive fill which will result in an ignition or burn of the fill. Research by the NFESC and ARL concludes that the detonation threshold for a munition depends largely upon the thickness of the munition's casing. For thick case or robust munitions, this pressure can be directly related to the deformation of the munition's casing. However, the same relationship does not hold true for thin case munitions. For these munitions, the casing provides little resistance, and determination of valid threshold criteria for ignition are presently under development.

As a result of this research, the Navy is developing separate ignition criteria for thin and thick case munitions. In order to provide an exact definition of a thick case munition, this report considers only those munitions which satisfy the definition of a robust munition as being thick cased. Analytical results for robust and thin case munitions are provided in the following section.

3.3 Application of Method to Robust Munitions

Robust munitions have been defined as "Ammunition with a nominal wall thickness of at least 1 cm [0.394 inch] and a ratio of the explosives weight to empty case weight less than 1.00." [8] As a part of the nonstandard magazine study, the NFESC performed analyses, at CEHNC's request, in which the alternate analysis method was used to determine explosive limits for nonstandard magazines whose storage is limited to robust munitions only. [9] Analytical methods and results from the study are summarized in the remainder of this section.

Using data from previous research, the NFESC identified the most sensitive robust munitions. In their study, detailed hydrocode analyses were used to determine the response of these munitions to impact by worst case secondary fragmentation from a magazine headwall. The loading on the headwall was calculated based on the detonation of 500,000 pounds NEW in a donor magazine sited at the present minimum separation distances for a standard magazines

Charge Weight (lbs. TNT)	Headwall Thickness (in)	Impulse on Headwall (psi-msec)	Maximum Velocity (Impulse/mass) (ft/sec)
250,000	12	1429	44.2
	10	1429	53.0
	8	1429	66.3
	6	1429	88.3
300,000	12	1518	46.9
	10	1518	56.3
	8	1518	70.4
	6	1518	93.9
350,000	12	1598	49.4
	10	1598	59.3
	8	1598	74.1
	6	1598	98.8
400,000	12	1671	51.7
	10	1671	62.0
	8	1671	77.5
	6	1671	103.3
450,000	12	1738	53.7
	10	1738	64.5
	8	1738	80.6
	6	1738	107.5
500,000	12	1800	55.6
	10	1800	66.8
	8	1800	83.5
	6	1800	111.3

Table 1 - Maximum headwall secondary fragment velocity for acceptor magazine in rear to front configuration at a separation distance of $2.0 W^{1/3}$.

Charge Weight (lbs. TNT)	Headwall Thickness (in)	Impulse on Headwall (psi-msec)	Maximum Velocity (Impulse/mass) (ft/sec)
250,000	12	932	28.8
	10	932	34.6
	8	932	43.2
	6	932	57.6
300,000	12	1024	31.7
	10	1024	38.0
	8	1024	47.5
	6	1024	63.3
350,000	12	1113	34.4
	10	1113	41.3
	8	1113	51.6
	6	1113	68.8
400,000	12	1194	36.9
	10	1194	44.3
	8	1194	55.4
	6	1194	73.8
450,000	12	1264	39.1
	10	1264	46.9
	8	1264	58.6
	6	1264	78.2
500,000	12	1333	41.2
	10	1333	49.4
	8	1333	61.8
	6	1333	82.4

Table 2 - Maximum headwall secondary fragment velocity for acceptor magazine in rear to front configuration at a separation distance of 400 feet.

($1.25 \text{ W}^{1/3}$ side to side and $2.0 \text{ W}^{1/3}$ rear to front). The analyses considered worst case secondary fragments from the headwall, pilaster, and door. In the study, three door types were considered; analyses were performed assuming impact by the heaviest, "worst case" door, a 10' x 11' sliding door with a total mass of 4,600 pounds.

The results of the NFESC study are as follows. The most sensitive robust munitions are the M107-155mm projectile and MK 82 bomb. Since the MK 82 bomb can be easily stored beyond the current nonstandard magazines storage limit of 250,000 pounds NEW, hydrocode analyses concentrated on this munition. In all cases, the maximum deformation and internal pressure in the munition were well below the established reaction thresholds. Consequently, no sympathetic reaction was expected.

Based on the NFESC study, if only robust munitions are stored in potential acceptor magazines, the standard magazine explosive limit of 500,000 pounds and the standard intermagazine separation distances may be safely applied to nonstandard magazines. Before applying standard magazine criteria, however, the door weight and the headwall construction should be checked to verify that they are within the range of values considered in the NFESC study.

3.4 Application of Method to Thin Case Munitions

Unlike the response of robust munition casings, the casing on thin case munitions provides little resistance, and threshold criteria for ignition are presently under development. It appears likely, however, that rather than case deformation, the criteria will be based upon the unit impulse (or momentum) and unit energy imparted to the munition. [10]

The ARL has performed tests on a limited group of potential worst case explosive acceptors. As expected, test results have shown that thin case munitions are much more sensitive than robust munitions to ignition or burning. Ignition of the thin case munitions considered in the test program has occurred at impact velocities as low as 24 meters per second (79 feet per second) and detonation has resulted at impact velocities as low as 30 meters per second (98 feet per second). [11]

Comparison of these limited data to the maximum headwall debris velocities of Table 1 shows that at minimum standard magazine separation distances, the present explosive limit of 250,000 pounds cannot be safely increased for all nonstandard magazines unless some limitation is placed on the thin case munitions stored. Comparison with the maximum velocities in Table 2 reveals a more favorable condition. These results indicate that it may be possible to store much higher quantities of the thin case munitions considered by ARL if the magazines are sited at the larger nonstandard separation distances. Further research will be required to expand the test data for thin case munitions before explosive storage limits can be increased beyond that suggested by the current body of data.

4.0 CONCLUSIONS

Based on the foregoing discussion, the following conclusions are made:

1. At typical separation distances, storage limits for 652-1012 through 652-1014 series magazines cannot be increased by current TM 5-1300 deformation analysis. As discussed in section 2.1.1, these magazines were designed as a modification to the standard series 652-686 through 652-693 magazines with the specific goal of conserving critical wartime materials. At a rear to front separation distance of 400 feet, the storage limit for these magazines based on TM 5-1300 deformation criteria is approximately 75,000 pounds NEW.
2. In a very limited number of cases, the storage limit for a nonstandard ECM can be increased above the 250,000 pound NEW limit using TM 5-1300 methodologies. For example, the 100 double door magazines at Tooele Army Depot are of unusually substantial construction with both the 12-inch headwall and the door supported by pilasters. At separation distances of 180 feet side to side and 360 feet rear to front, the storage limit for these magazines may be increased to 500,000 pounds NEW using the TM 5-1300, deformation based methodologies. Unfortunately, as discussed in section 2.2.2, these magazines were placed between previously constructed series 652-1012 through 652-1014 magazines, and consequently, their explosive limit must be based on their potential role as a donor to these less substantial magazines. As a result, the storage limit for the 100 double door magazines cannot be increased above the present nonstandard magazine limit of 250,000 pounds NEW.
3. A new analysis method has been developed which, in many cases, will allow for the safe increase in storage limits of nonstandard ECMs. This method is based on preventing explosive propagation from impact by secondary fragmentation from an acceptor magazine's headwall. Under this method, the headwall of the acceptor magazine is allowed to fail. Secondary debris from the headwall is allowed to impact the munitions in the acceptor magazine, but the maximum velocity of these fragments is limited to a level at which explosive propagation will not occur. Some munitions near the headwall of the acceptor magazine, however, may be deformed by secondary fragment impact and may not be usable.
4. A robust munition has been defined as "Ammunition with a nominal wall thickness of at least 1 cm [0.394 inch] and a ratio of the explosives weight to empty case weight less than 1.00." [8] Under the High Performance Magazine Program, the Navy has developed explosive sensitivity criteria for the more sensitive, "worst case," robust munitions. Based on these criteria and on further hydrocode analyses by NFESC, an explosion will not propagate to robust munitions in a nonstandard ECM even if the magazine is sited at **minimum standard ECM separation distances** from a donor magazine storing 500,000 pounds NEW. Consequently, if only robust munitions are stored in any potential acceptor magazine, the donor magazine may safely employ standard ECM explosive limit and separation distances. Before applying standard ECM criteria, however, it is recommended that the door weight and headwall construction be checked to verify that they are within the range of values considered in the NFESC study.

5. For non-robust munitions, the alternate analysis method indicates that it may be possible to increase storage limits for nonstandard ECMs sited at the greater, nonstandard separation distances. However, to take advantage of this potential on a widespread basis, additional testing of non-robust or thin case munitions must be completed in order to define the initiation threshold for these munitions. As expected, non-robust or thin case munitions are much more sensitive to ignition by fragment impact than robust munitions. In recent tests, ignition of a thin case munition has occurred at fragment impact velocities as low as 24 meters per second (79 feet per second), and detonation has resulted at impact velocities as low as 30 meters per second (98 feet per second). Comparing these limited data with Table 2 indicates the likelihood that some increase in storage capacities is possible for nonstandard sitings, but at this time, it must be considered on a case by case basis.

5.0 RECOMMENDATIONS

1. The DOD Ammunition and Explosives Safety Standards, DOD 6055.9-STD, should be revised to allow the use of standard ECM storage limits and minimum separation distances for nonstandard ECMs provided that the following conditions are satisfied: (1) all potential acceptor magazines will store only robust munitions and (2) the owner/operator is willing to accept limited damage to potential acceptor munitions.
2. For those cases in which limited damage to an acceptor munition is not acceptable, the current DOD 6055.9-STD requirements for nonstandard ECMs should be retained. This recommendation is particularly applicable to munitions which would be difficult or costly to replace.
3. Further research and safety criteria are required prior to the development of new explosive storage limits for non-robust or thin case munitions. In particular, a decision is needed as to what constitutes an acceptance outcome, e.g. is the burn of an acceptor munition acceptable.
4. Complete lists should be developed of all munitions which, based on available storage volume, can exceed the 250,000 lb. NEW storage limit in 60'-8" and 81'-0" long, arch-type ECMs. The total quantity of these munitions in the storage inventory should then be determined. Through so doing, the impact of increased storage limits for nonstandard magazines can be more accurately assessed, and research on munition sensitivity can be prioritized based upon the munitions which would derive the greatest benefit from increased storage limits.
5. In accordance with TM 5-1300, design concepts should be developed for modifying series 652-1012 through 652-1014 magazines which, if implemented, would allow the use of standard ECM safety criteria for these magazines. Due to the large number of these type magazines, the potential impact on storage capacity is substantial. In addition, since the cost of modifying an existing series 652-1012 through 652-1014 magazine will likely be significantly less than the cost of building a new magazine, and no new land area, support infrastructure, or additional security would be required, the cost-benefit ratio would be substantial.

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